Production of highly-charged ions in an EBIT

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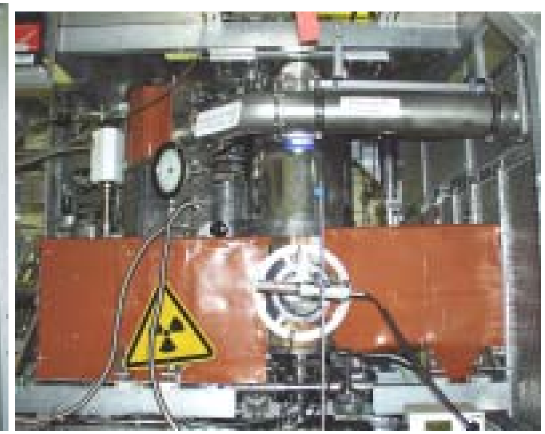
1. **Production of highly charged ions**
2. **Results**
3. **Outlook**



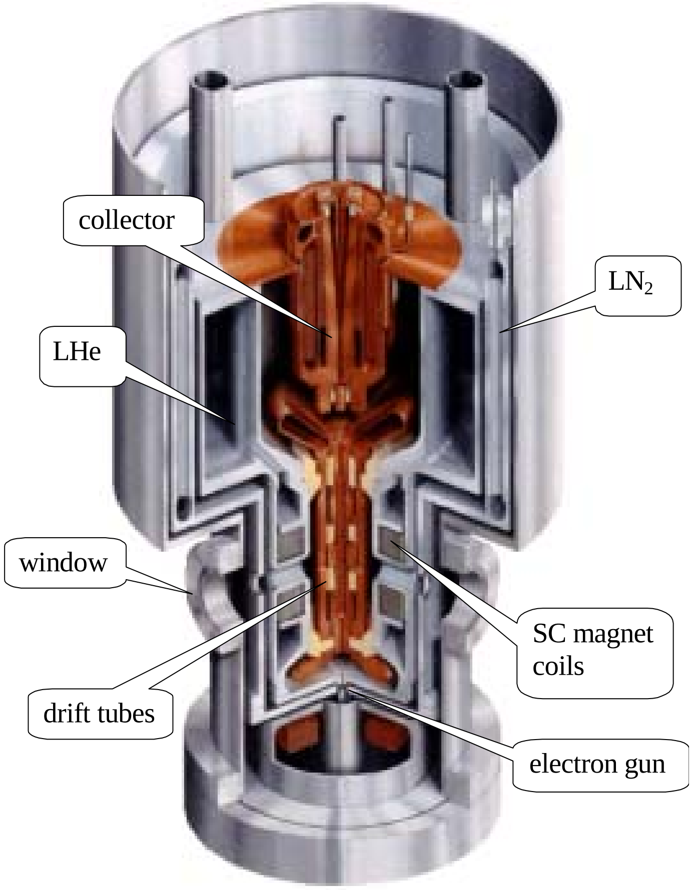






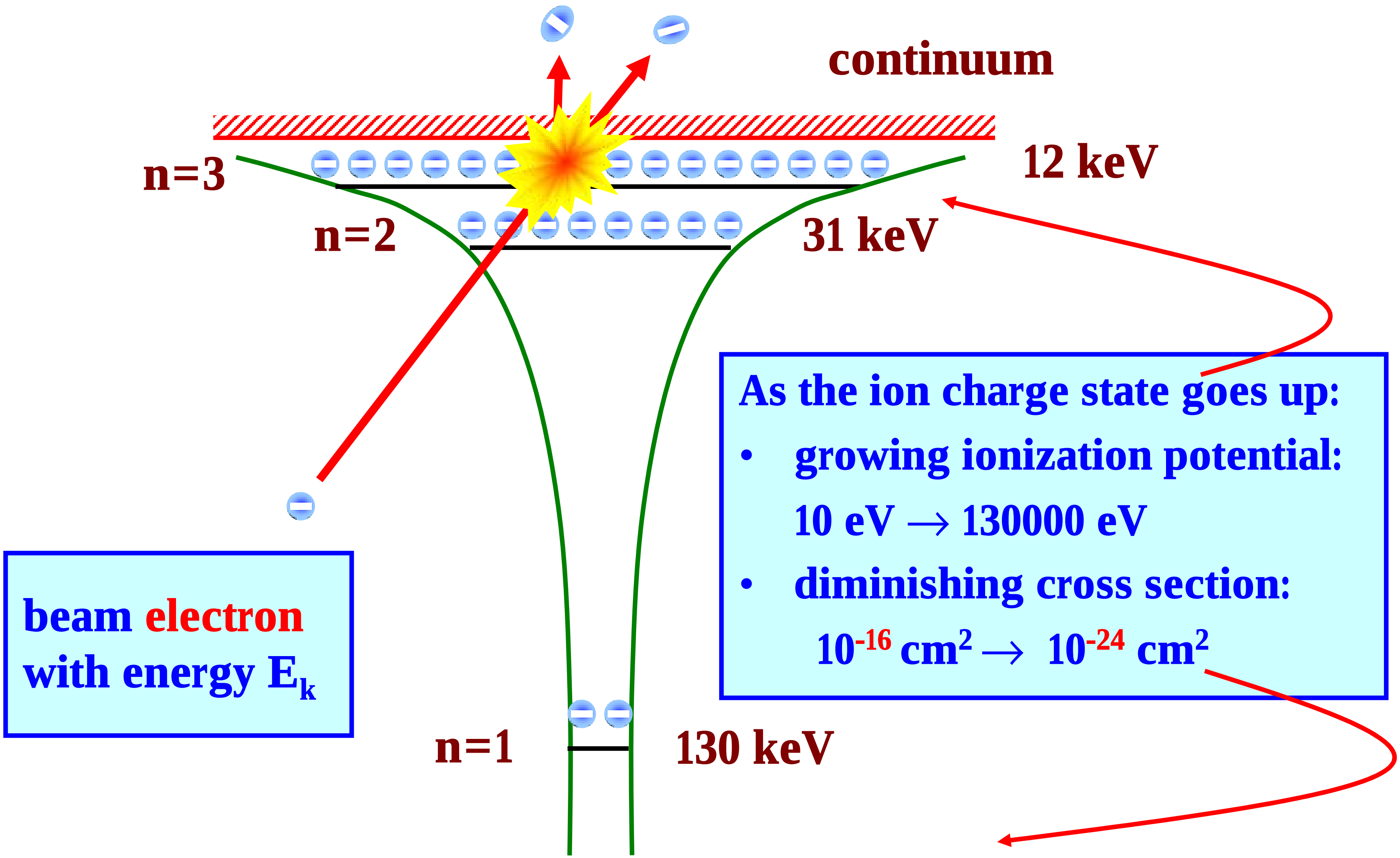
A little bit of history…

The electron beam ion trap (EBIT) was developed at the Lawrence Livermore National Laboratory (LLNL) in the late 1980s by R. Marrs and M. Levine

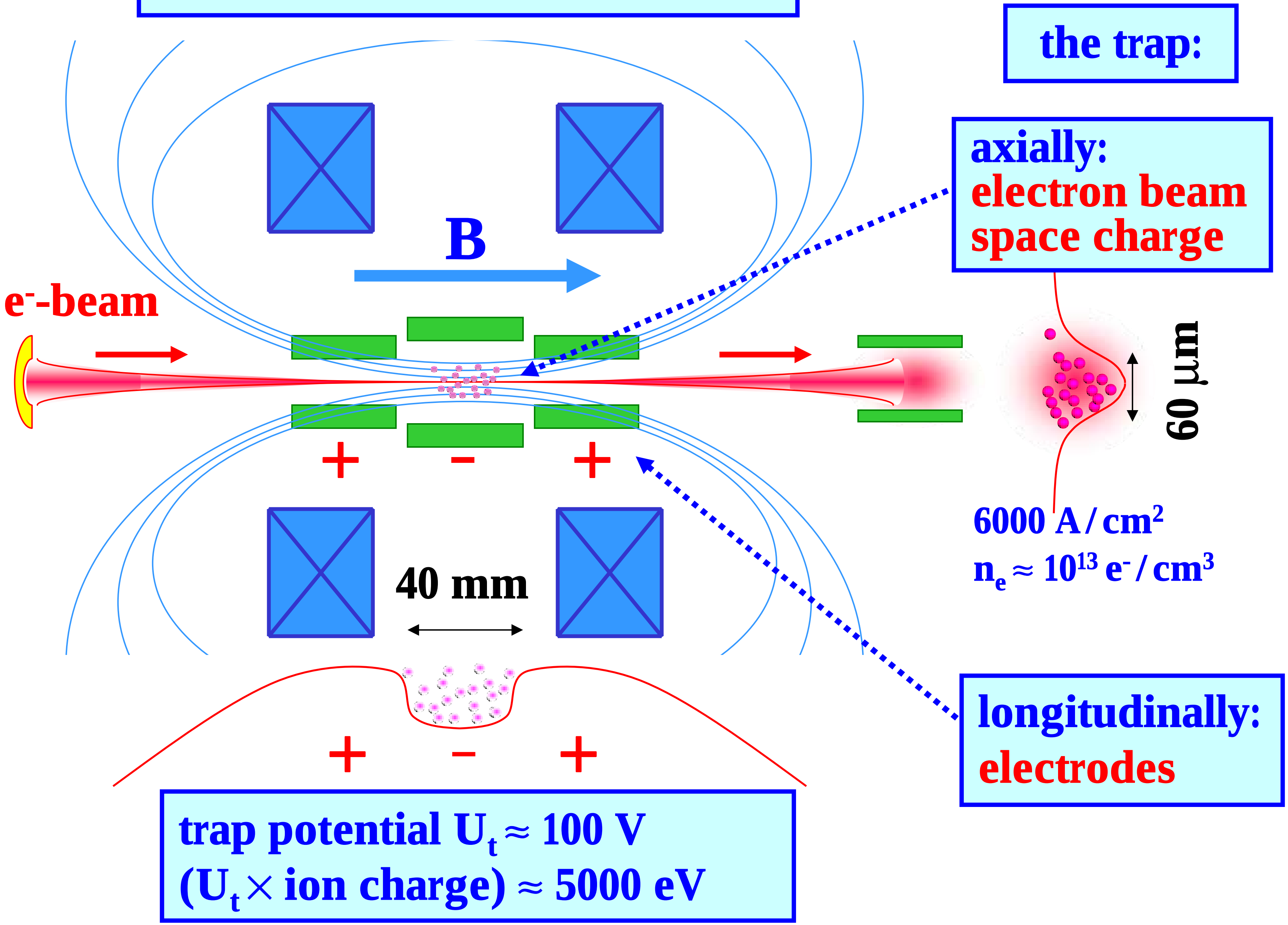


EBIT II

Sequential electron impact ionization in an electron beam ion trap

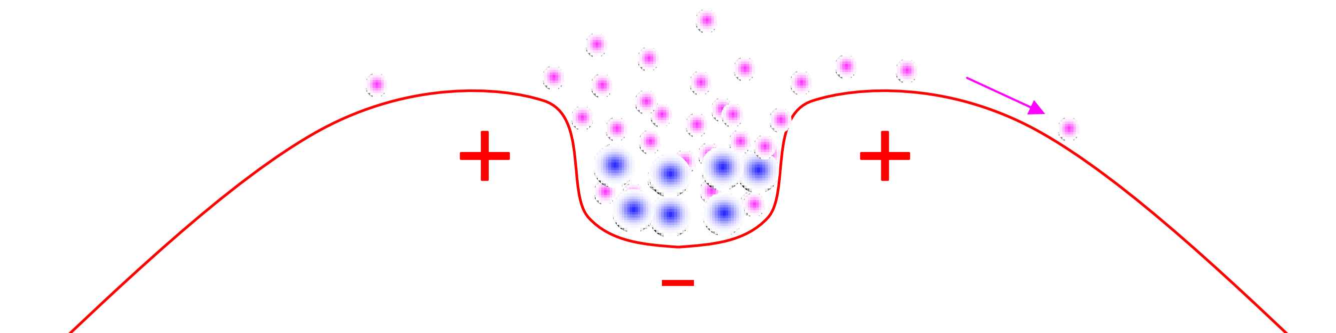


EBIT (*electron beam ion trap*)



Evaporative cooling

- collisions with beam electrons heat up ion ensemble
- light, less tightly trapped ions (e.g. Ne^{10+}) evaporate removing thermal energy



- heavy, highly charged ions (e.g. Ba^{53+}) remain trapped

Ion temperature from 1000 eV to 30 eV

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Doppler width $\Delta\lambda/\lambda \approx 1/20.000$ (Ba^{53+})

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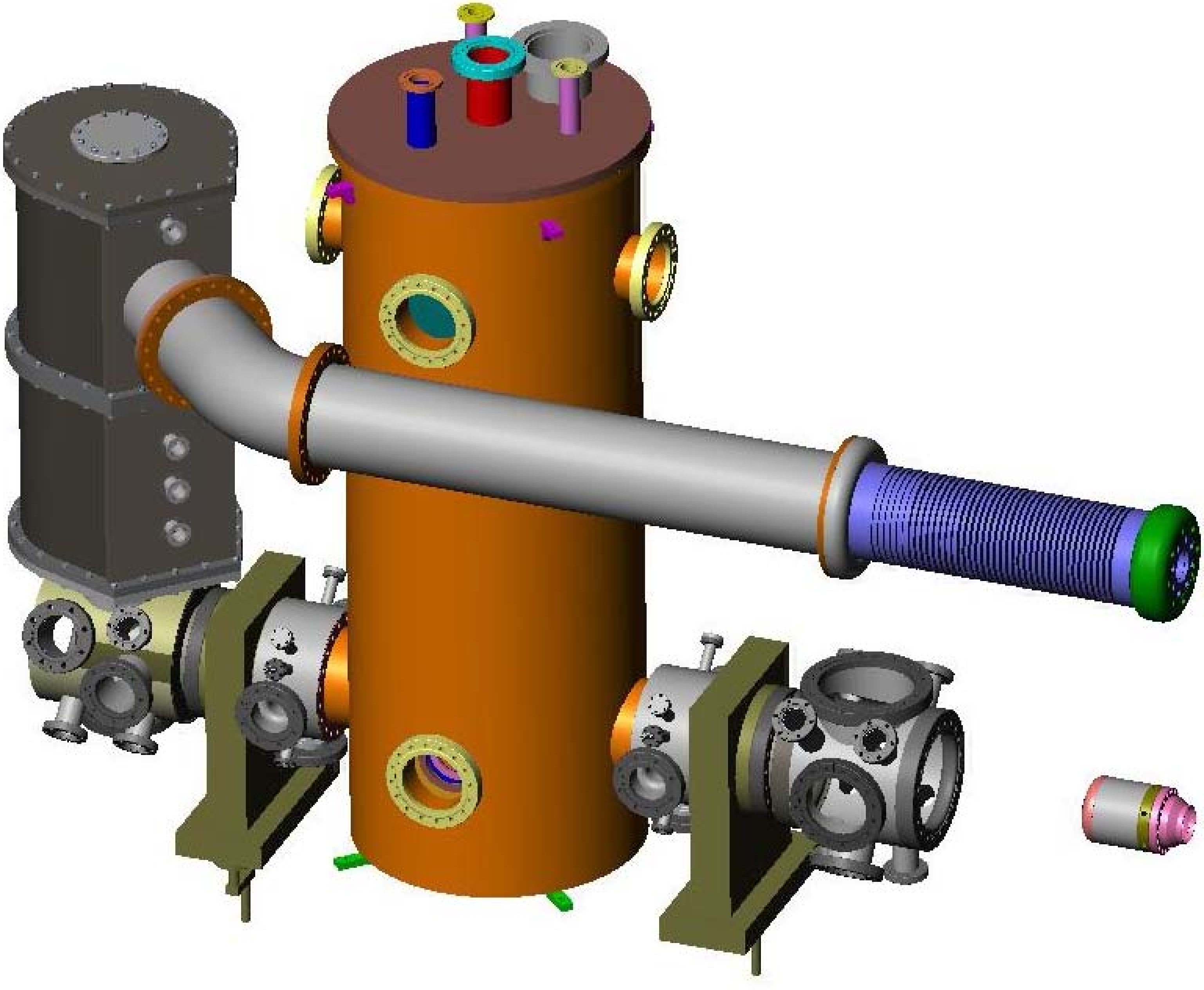
High resolution spectroscopy

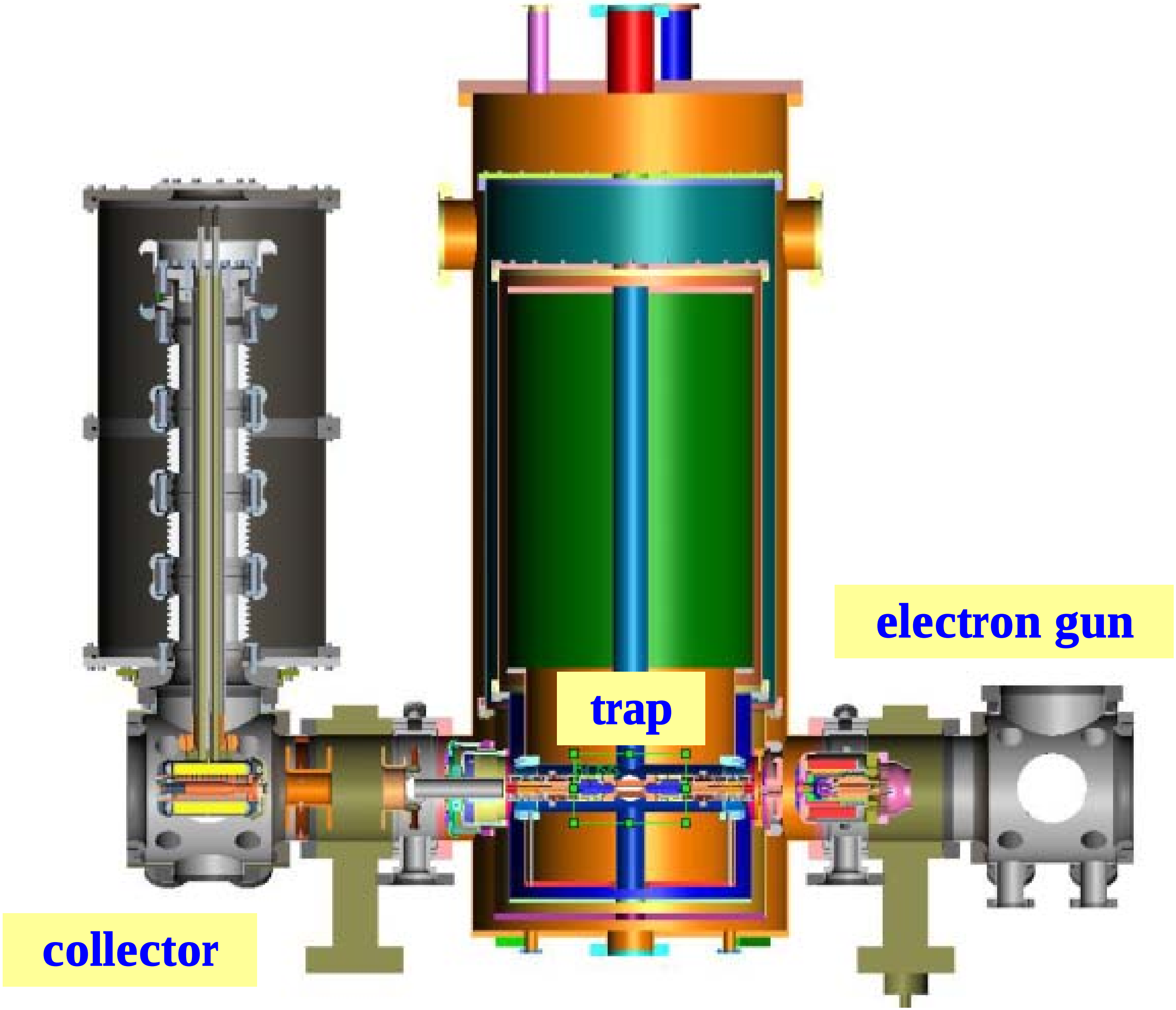
Other (possible) cooling methods:

- **resistive cooling**
- **sympathetic cooling**

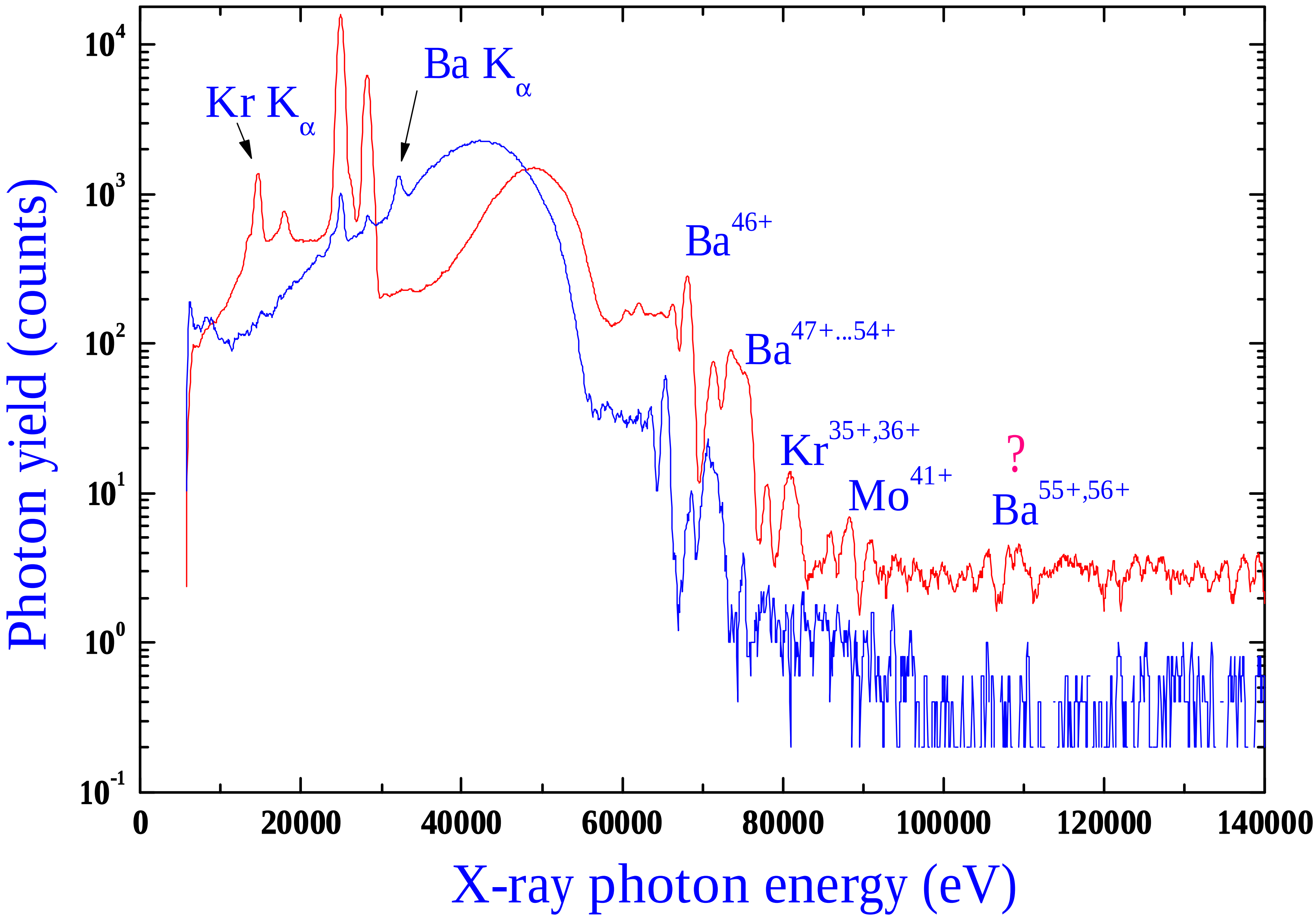
have beeing applied to HCI in external Penning traps (RETRAP, LLNL EBIT, D. Schneider).

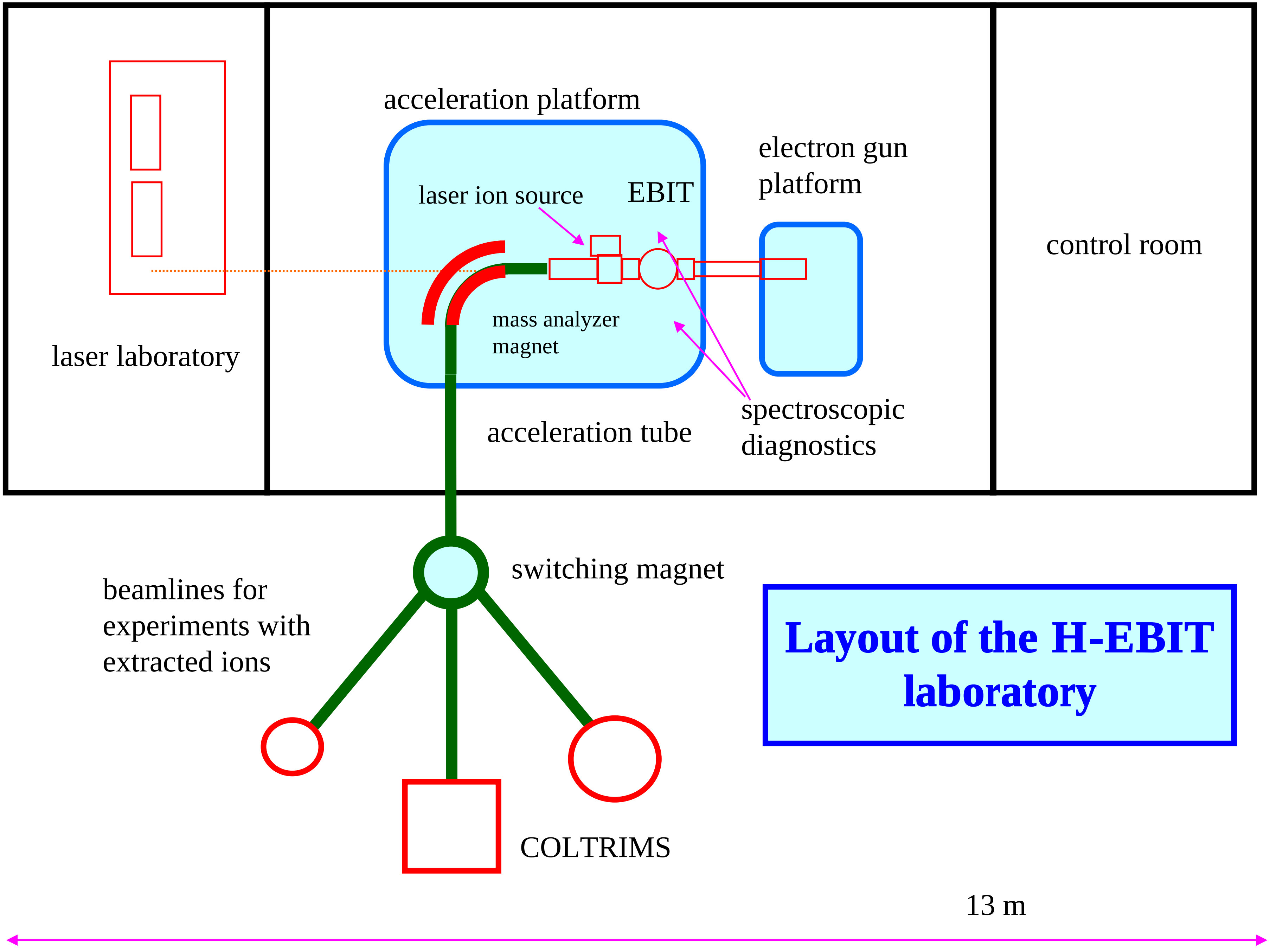
Typical EBIT ion temperatures (2 eV/q) result in an excellent emittance ($1 \cdot \pi \cdot$mm$\cdot$mrad @ 8 keV/q) for low energy beams, allowing efficient beam transport.




electron gun
trap
collector

Status: beam energy up to 100 keV, beam currents up to 360 mA, HV tests up to 125 kV...but still fighting around Ba^{54+}





acceleration platform
electron gun
platform
laser ion source
EBIT
control room
mass analyzer
magnet
laser laboratory
spectroscopic
diagnostics
acceleration tube
switching magnet
beamlines for
experiments with
extracted ions
Layout of the H-EBIT
laboratory
COLTRIMS
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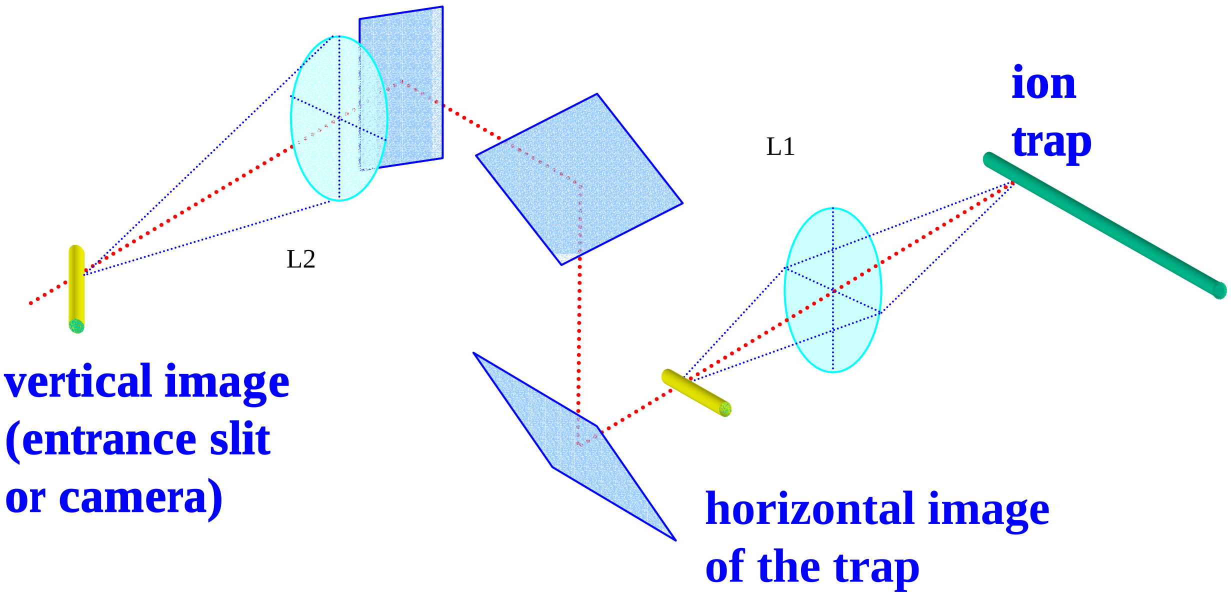
Results:

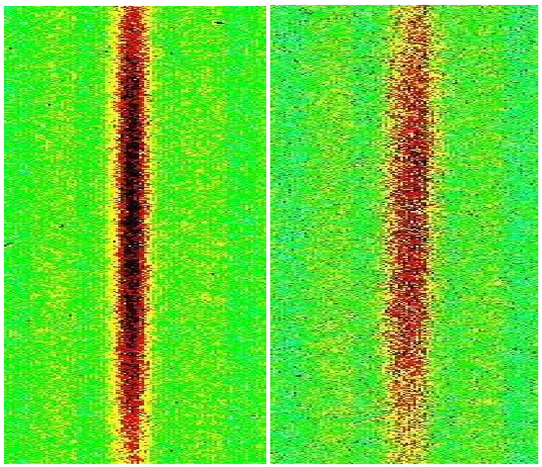
Optical spectra: forbidden transitions

Dielectronic recombination

Ion-atom collisions

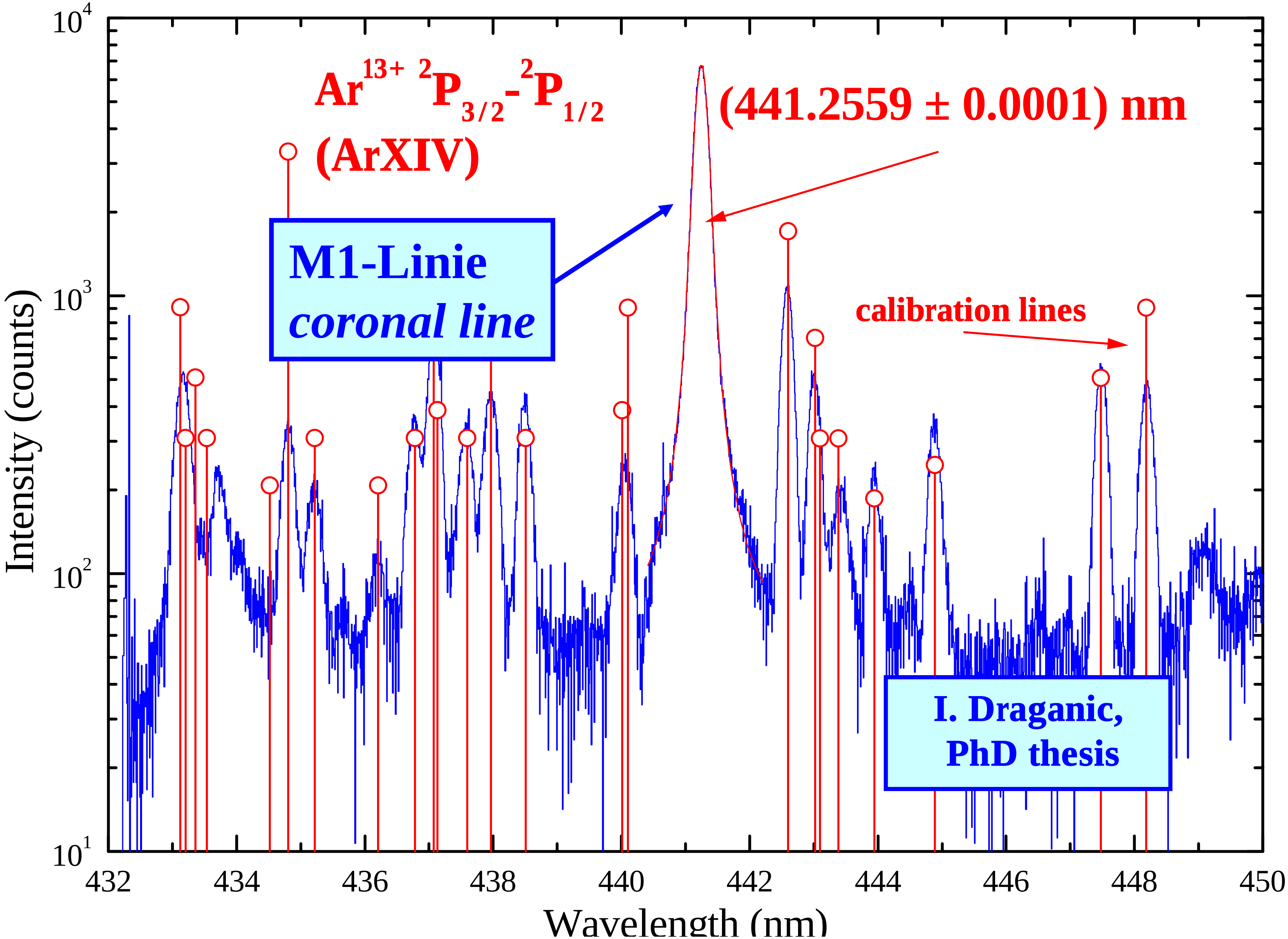
Imaging the trapped ions



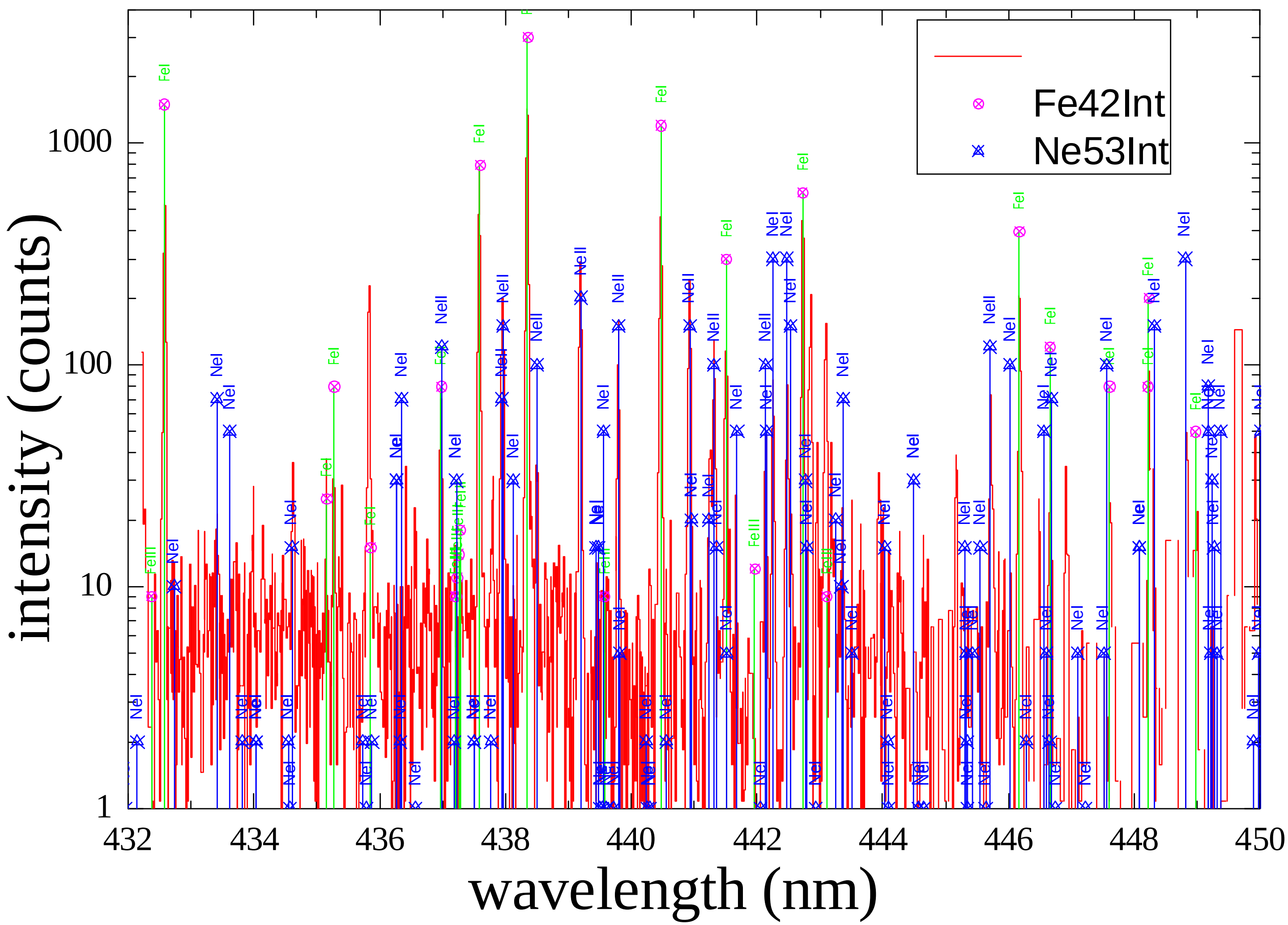


trapped ions: left, Ar^{13+} ; right Ar^{9+}.
The ion cloud has ≈ 0.3 mm diameter.

Forbidden transitions in the visible range



Extensive and repeated measurements and calibrations are necessary to exclude systematic errors and drifts



Wavelength determination with highest precision

Ion	Transition	Experiment (nm)	Theory (nm)	Present Measurement
Ar^{+9}	$2s^2 2p^5\ ^2P_{3/2} - ^2P_{1/2}$	553.34(4) [1]	553.39(21) [1]	553.3265(2)
Ar^{+10}	$2s^2 2p^4\ ^3P_2 - ^3P_1$	691.686(6) [2]	693.1(2.4) [1]	691.6878(2)
Ar^{+13}	$2s^2 2p\ ^2P_{1/2} - ^2P_{3/2}$	441.250(3) [2]	441.6(4) [1]	441.2559(1)
Ar^{+14}	$2s2p\ ^3P_1 - ^3P_2$	594.373(4) [2]	594.4(2.5) [1]	594.3880(3)
Kr^{+18}	$3p^2\ ^3P_2 - ^3P_1$	402.69 [3]	411.2 [3]	402.7143(3)
Kr^{+22}	$3p^5\ 3d^1\ ^3P_2 - ^3P_1$	384.26 [3]	384.5 [3]	384.1146(2)

1. V. Kaufman, J. Sugar, J.Phys. Chem. Ref. Data, Vol. 15, No 1, 1986 (321)
2. D.J. Bieber, H. Margolis, P. Oxley, J.D. Silver, Phys. Scr. Vol. T73, 1997 (64)
3. J.R. Crespo, P. Beiersdorfer, K. Widmann, V. Decaux, Phys. Scr. Vol. T80, 1999 (448)

I. Draganic, PhD thesis, submitted to PRL

Four and five electron systems show large sensitivity to QED contributions

Ion	CIDF (cm^{-1})	QED (cm^{-1})	Total (cm^{-1})	QED (nm)	Theory, (nm, air)	Experiment, (nm, air)
Ar^{+13}	22612.8(12.0)	49.5(7.0)	22662(14)	-0.96	441.14(27)	441.2559(1)
Ar^{+14}	16770.9(3.0)	53.4(8.0)	16824.3(8.5)	-1.89	594.22(30)	594.3880(3)

RR → time reversed photoionization

as the electron beam energy changes:
→ Photon energy shifts continuosly

DR → time reversed Auger decay

as the electron beam energy changes:
→ carachteristic dielectronic resonances
→ selectively excited lines

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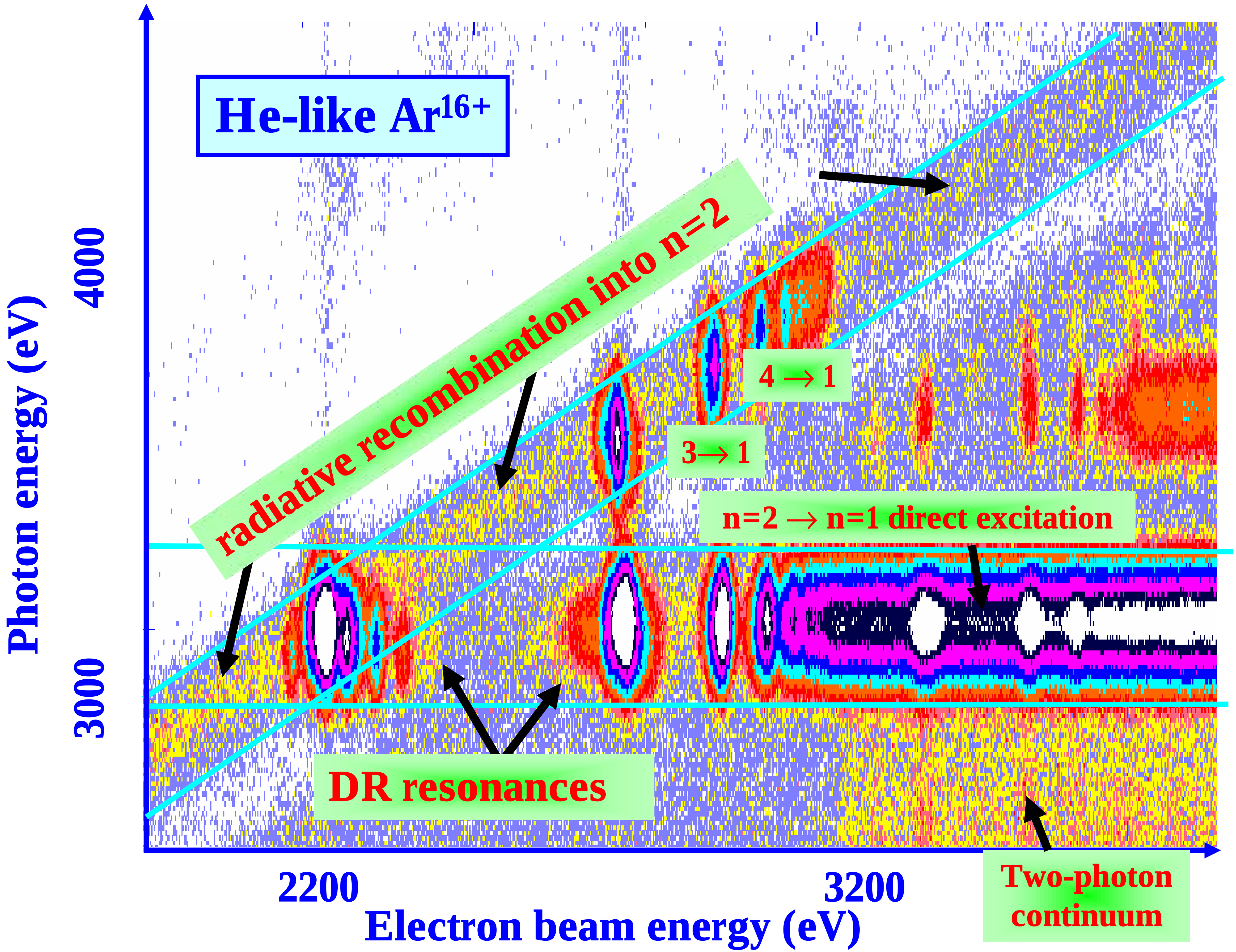
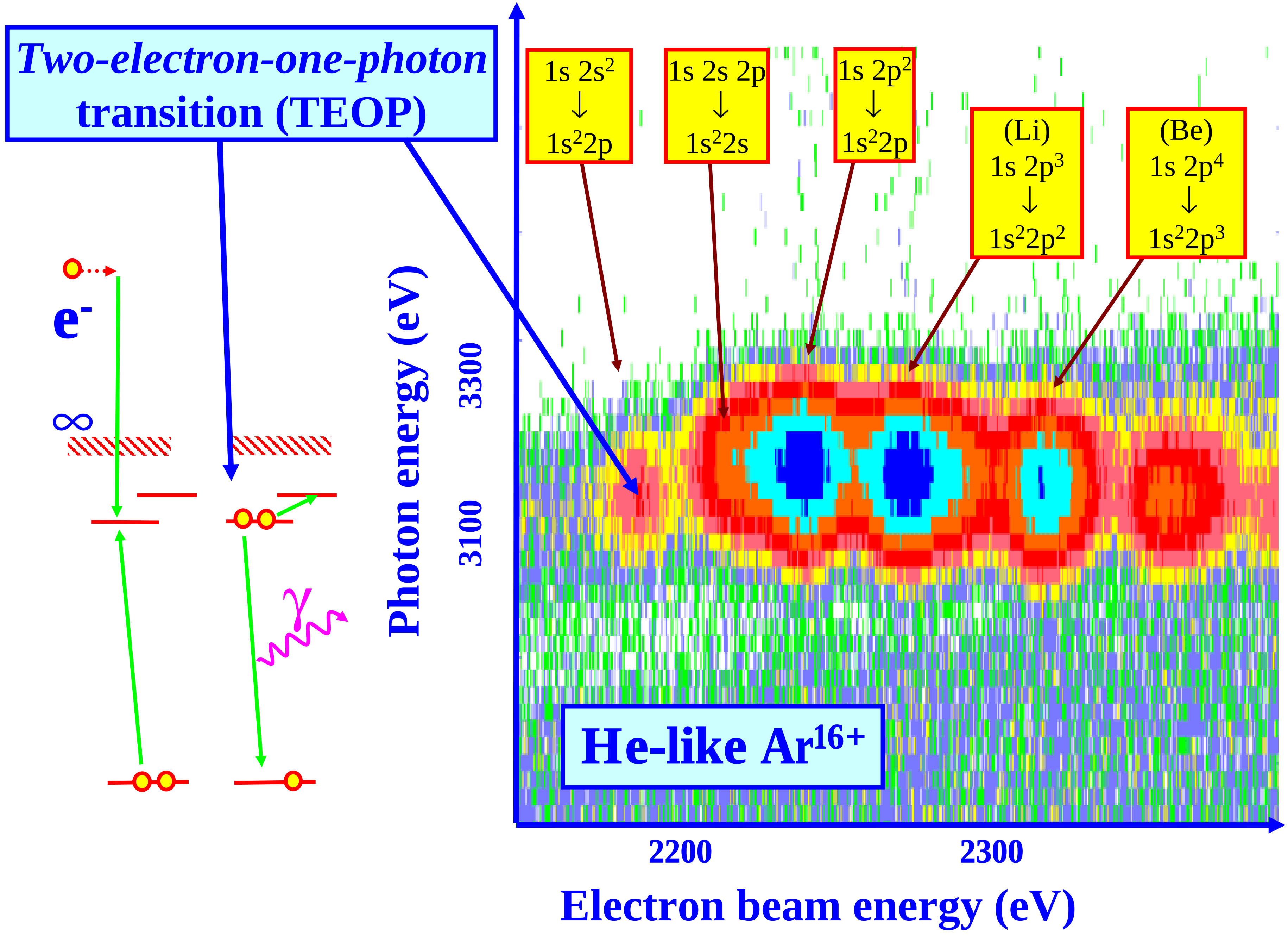
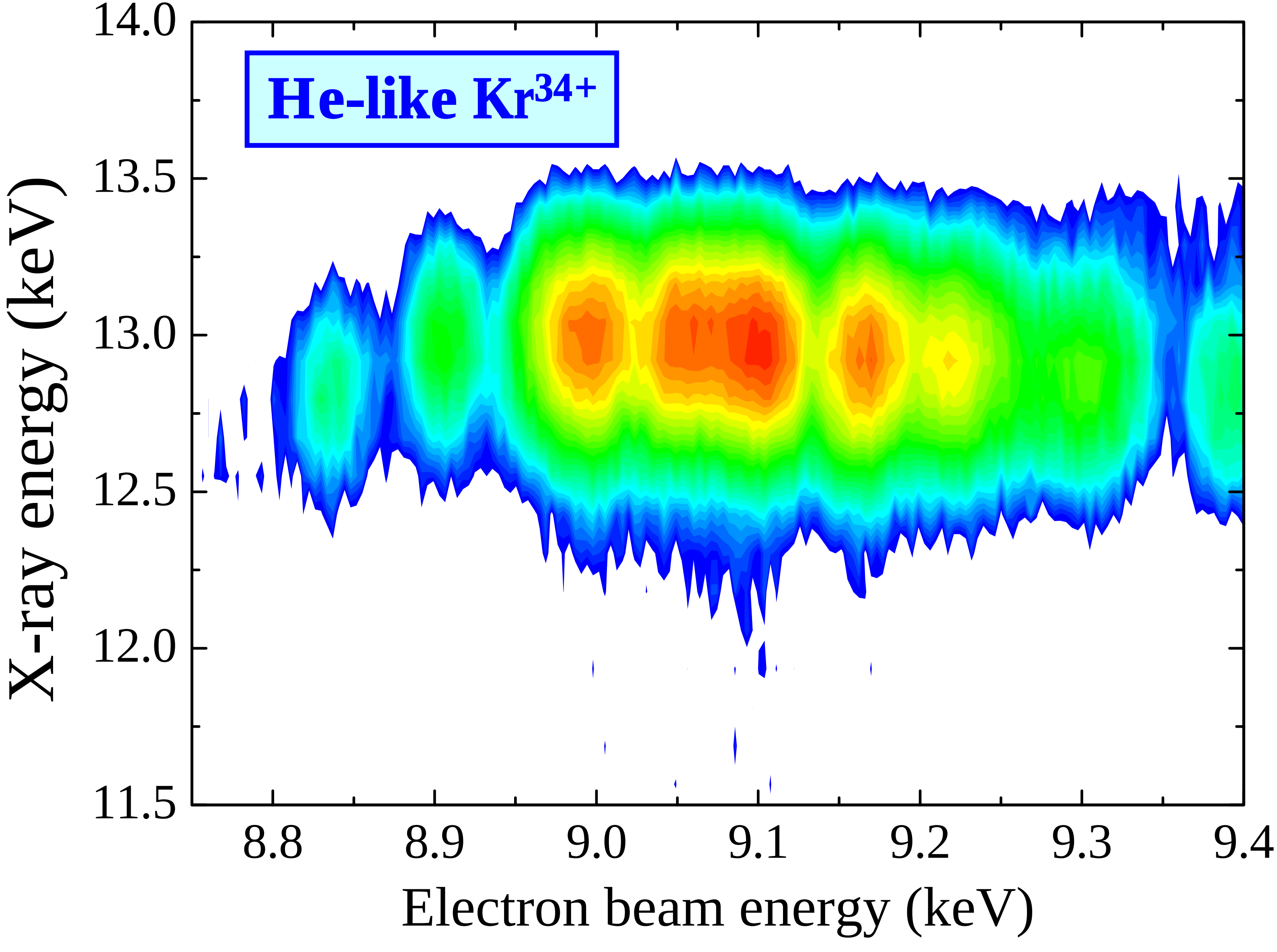
Experiment:

- **vary electron beam energy (x-coordinate)**
- **measure photon energy (y-coordinate)**

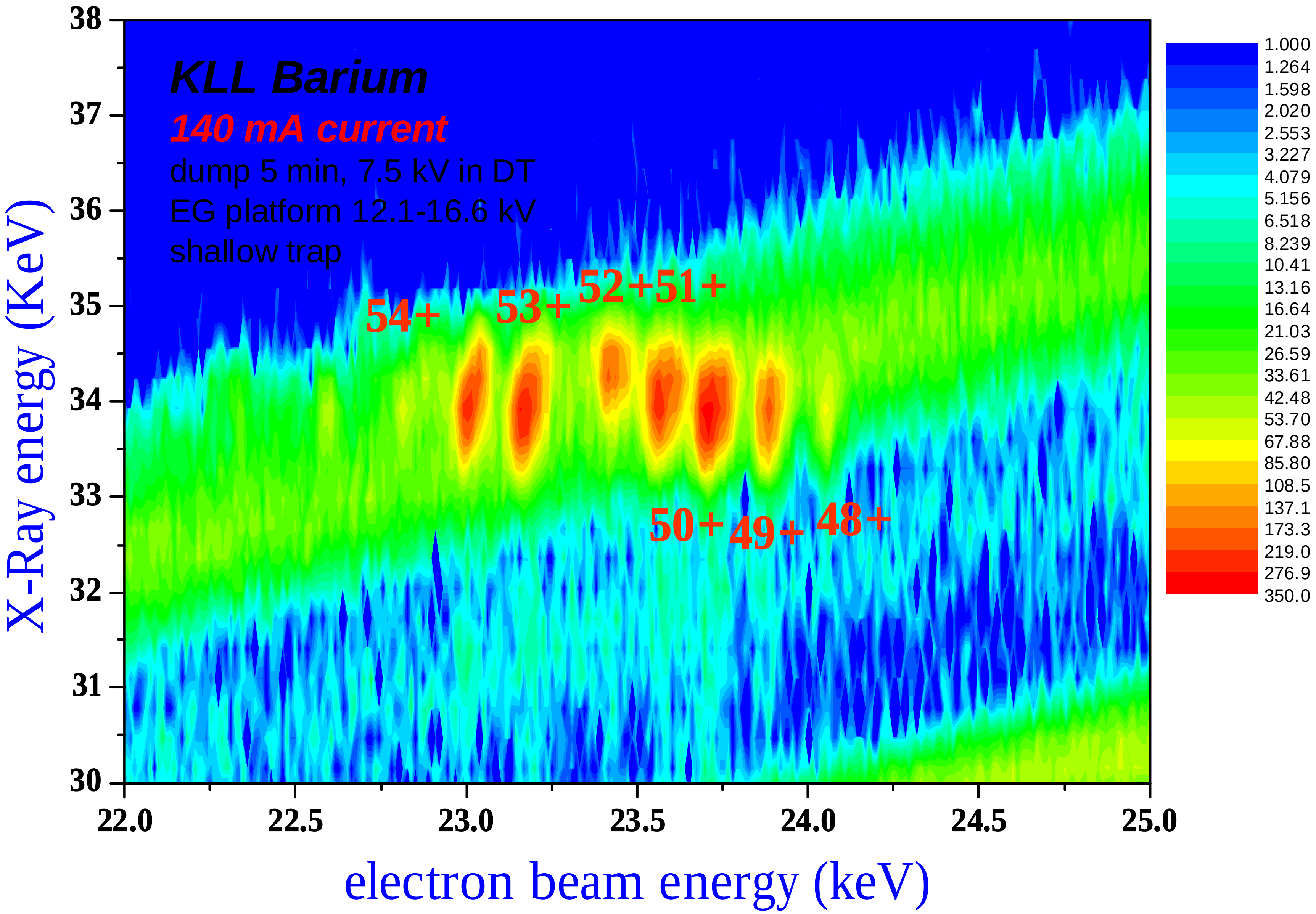

He-like Ar16+
radiative recombination into n=2
4→1
3→1
n=2 → n=1 direct excitation
DR resonances
Two-photon continuum
Photon energy (eV)
4000
3000
2200
3200
Electron beam energy (eV)



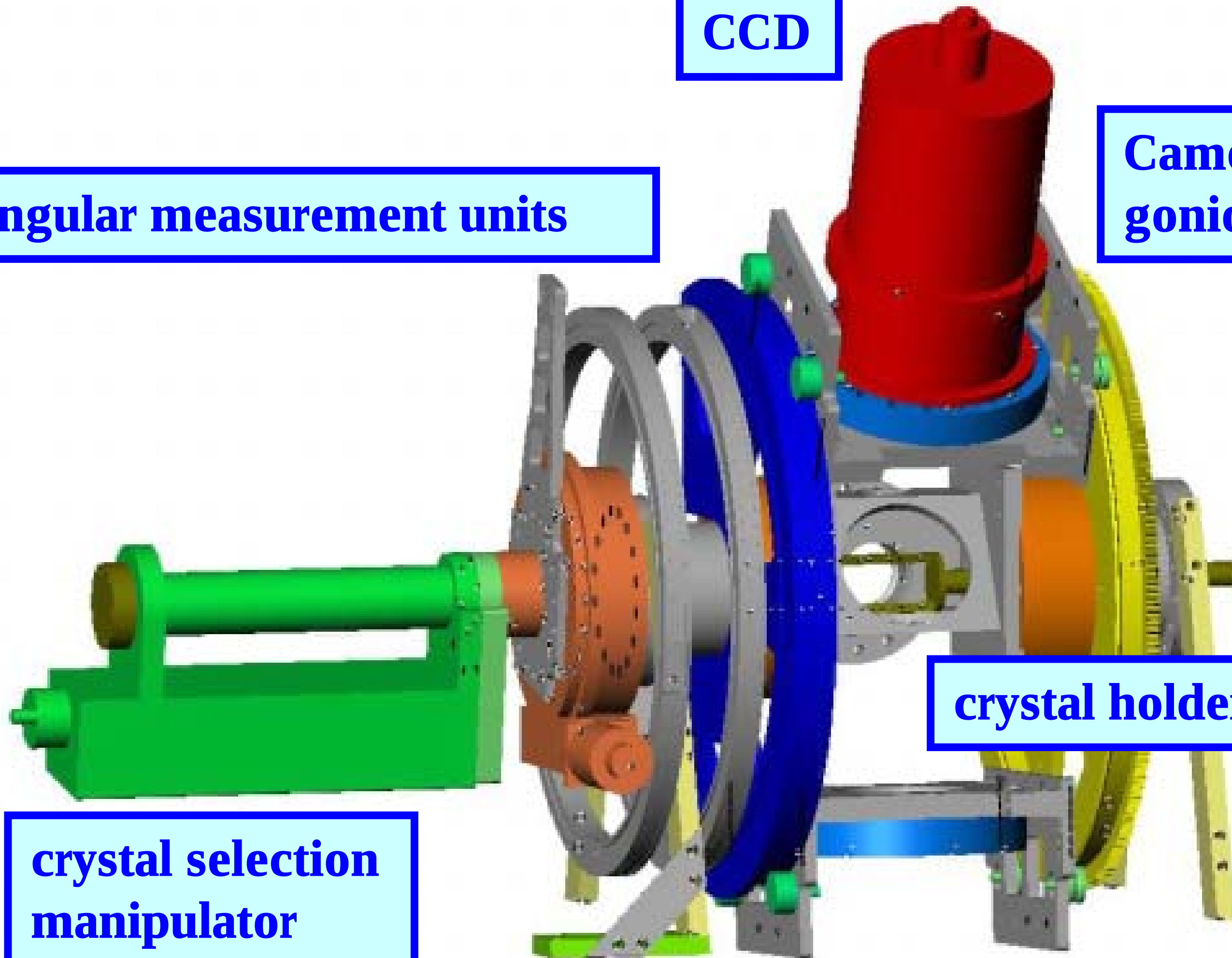
Two-electron-one-photon transition (TEOP)
e-
∞
γ
Photon energy (eV)
3300
3100
1s 2s2 ↓ 1s22p
1s 2s 2p ↓ 1s22s
1s 2p2 ↓ 1s22p
(Li) 1s 2p3 ↓ 1s22p2
(Be) 1s 2p4 ↓ 1s22p3
He-like Ar16+
2200
2300
Electron beam energy (eV)


He-like Kr^{34+}
14.0
13.5
13.0
12.5
12.0
11.5
X-ray energy (keV)
8.8
8.9
9.0
9.1
9.2
9.3
9.4
Electron beam energy (keV)

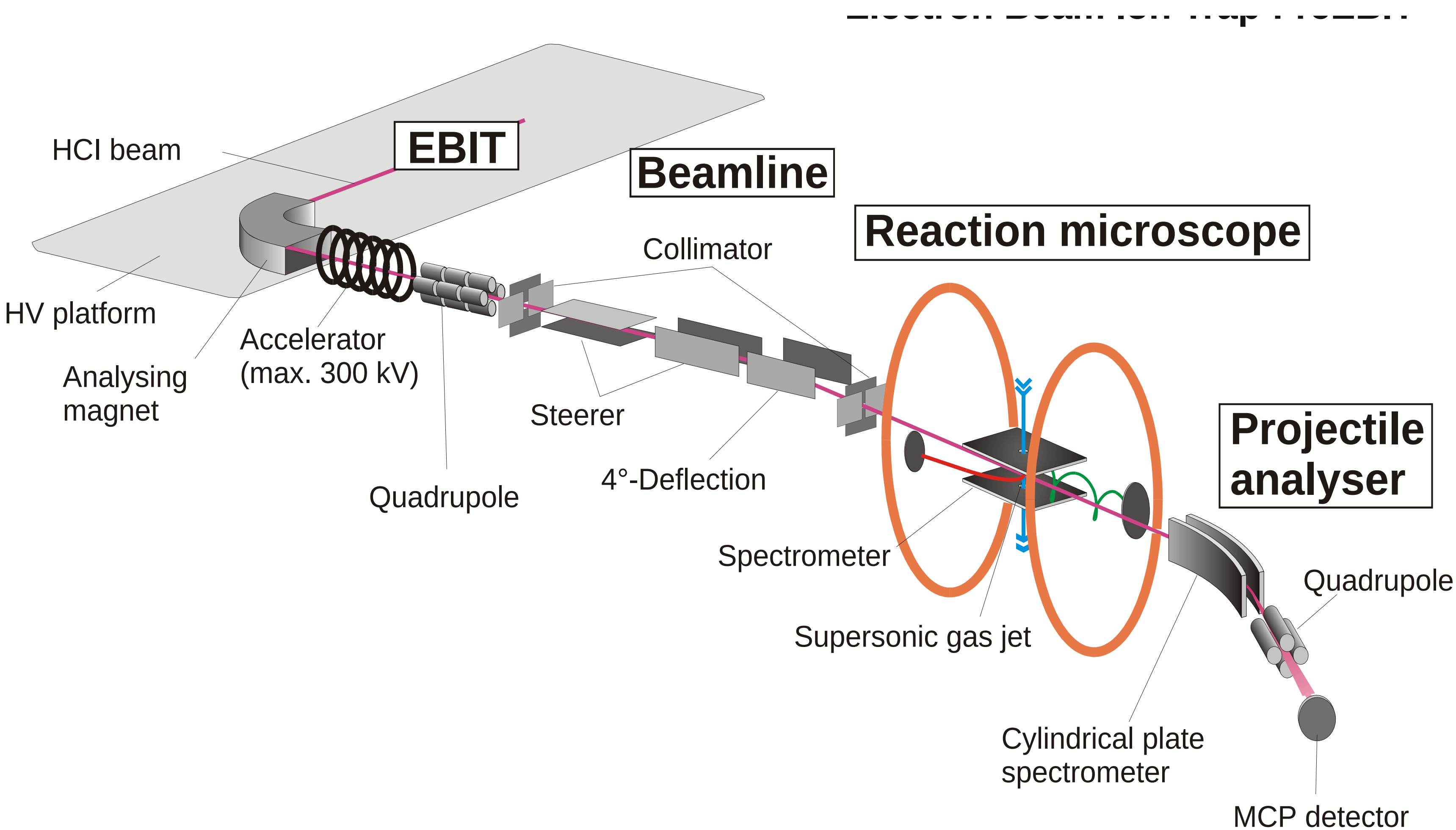
DR resonances of O-like to He-like Ba



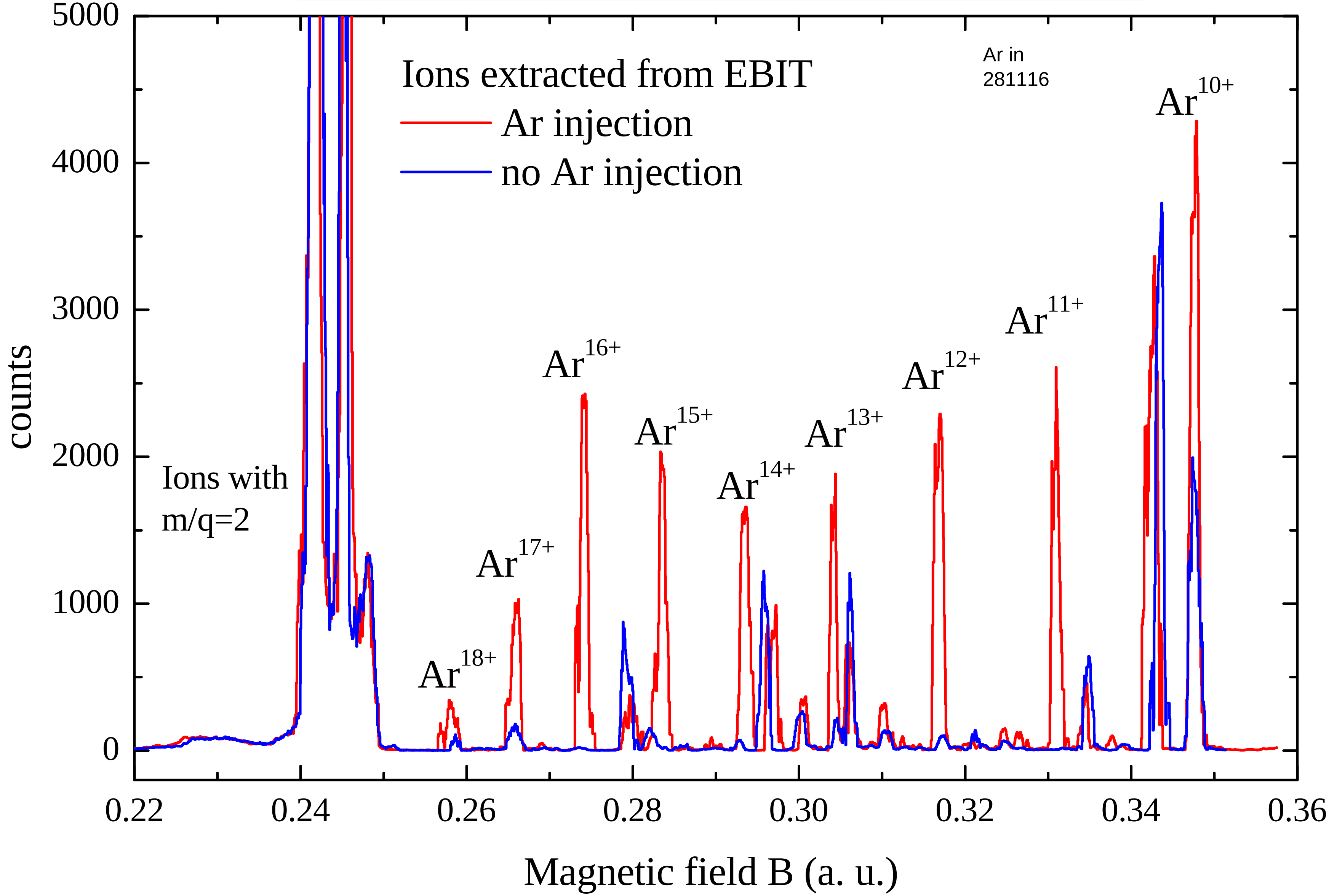
High resolution x-ray crystal spectrometer with cryogenic CCD detector, computer controlled (undergoing testing)

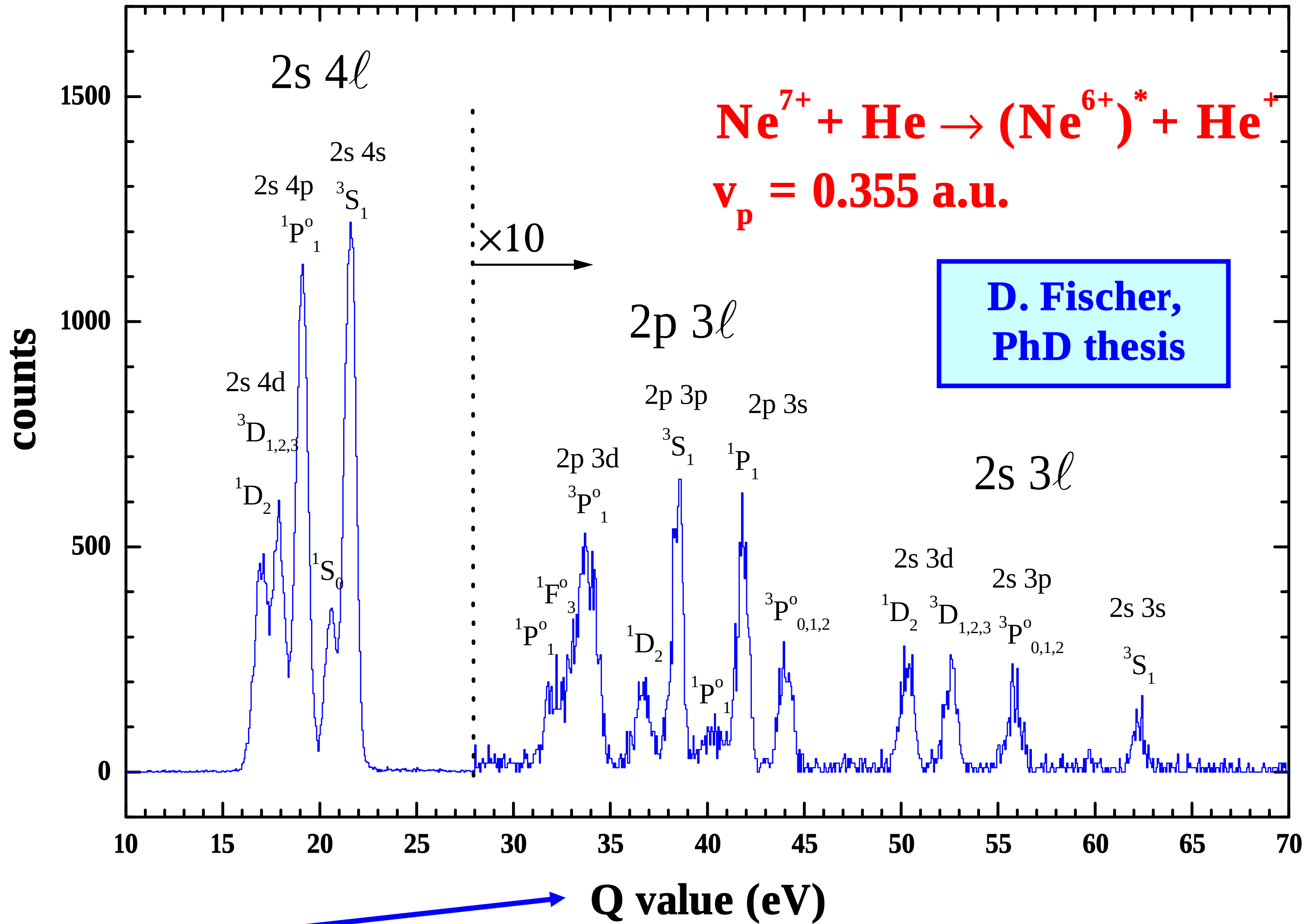


State selective measurements by COLTRIMS allows a kinematically complete measurement of the charge transfer reaction in ion-atom collisions



Extracted ions (first Heidelberg trials)

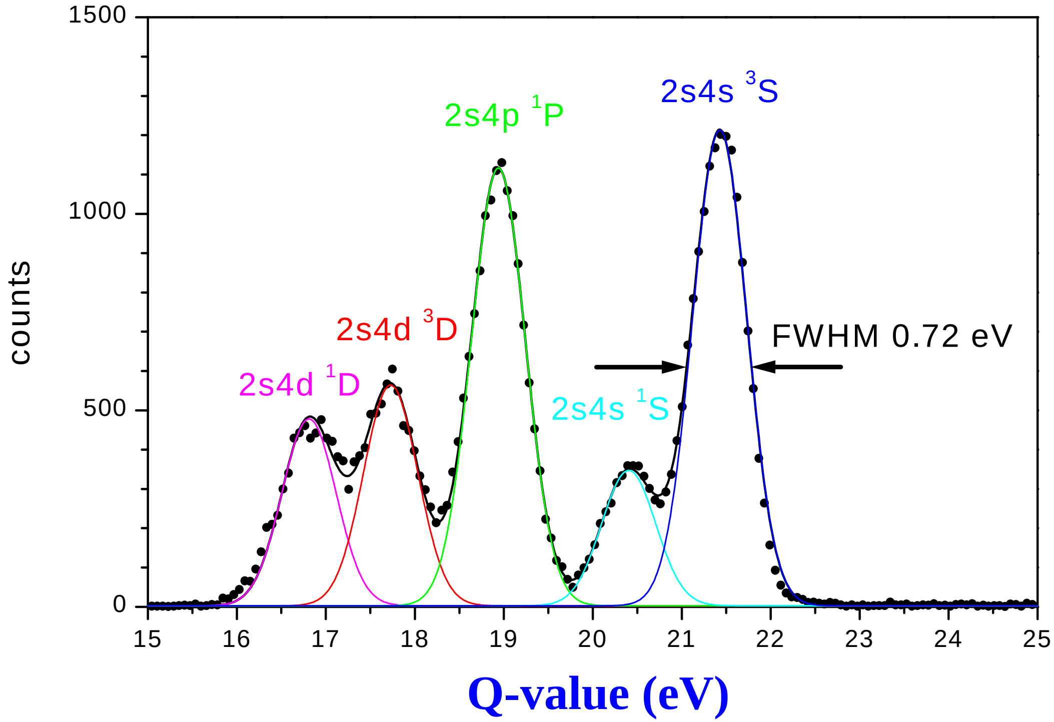




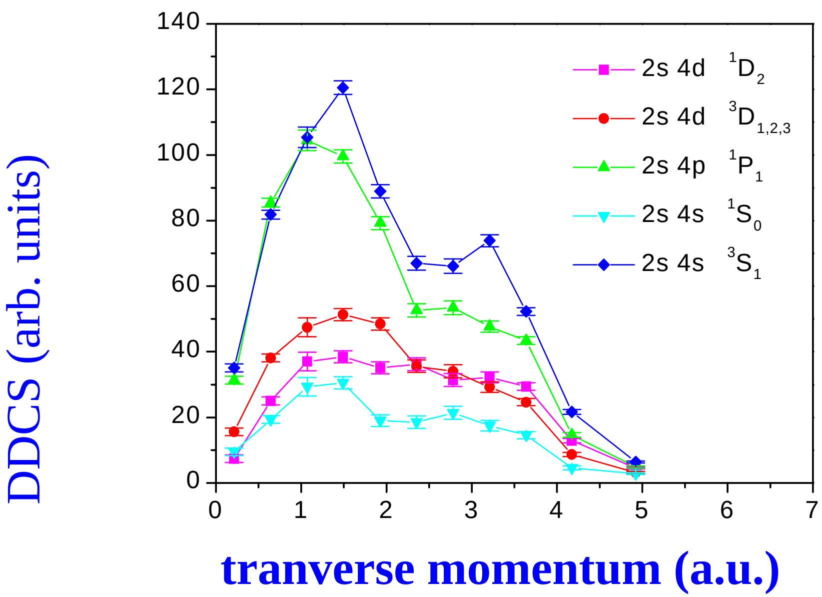
Q-value: energy transferred to the electronic system of the projectile and target during collision.

Resolution ≈ 1 eV FWHM → state selective

Resolution: 0.7 eV
Separation of subshells and spin states



D. Fischer, PhD thesis



Summary

- QED-sensitive forbidden transitions have been measured with excellent accuracy.
- Dielectronic recombination into deep levels has been observed in coincidence with photon emission up to Ba^{54+}.
- Collisions between HCI and neutrals have been studied with COLTRIMS, delivering state-selective data.
- High energy upgrade in progress, ion extraction working, instrumentation for high resolution x-ray spectroscopy...

Future: increase precision, energy and...

- Excitation with x-ray free electron laser : TESLA (beam time allocated)

EBIT team

Johannes Braun (diploma)
Hjalmar Bruhns (PhD)
Christina Dimoupoulou (post doc)
Antonio González Martínez (PhD)
Vladimir Mironov (post doc)
Rosario Soria Orts (PhD)
Hiro Tawara (post prof)
Michael Trinczek (post doc)
Joachim Ullrich

Currently visiting

Vladimir Shabaev
Ilija Tupyitsin
Chris Vankleeck

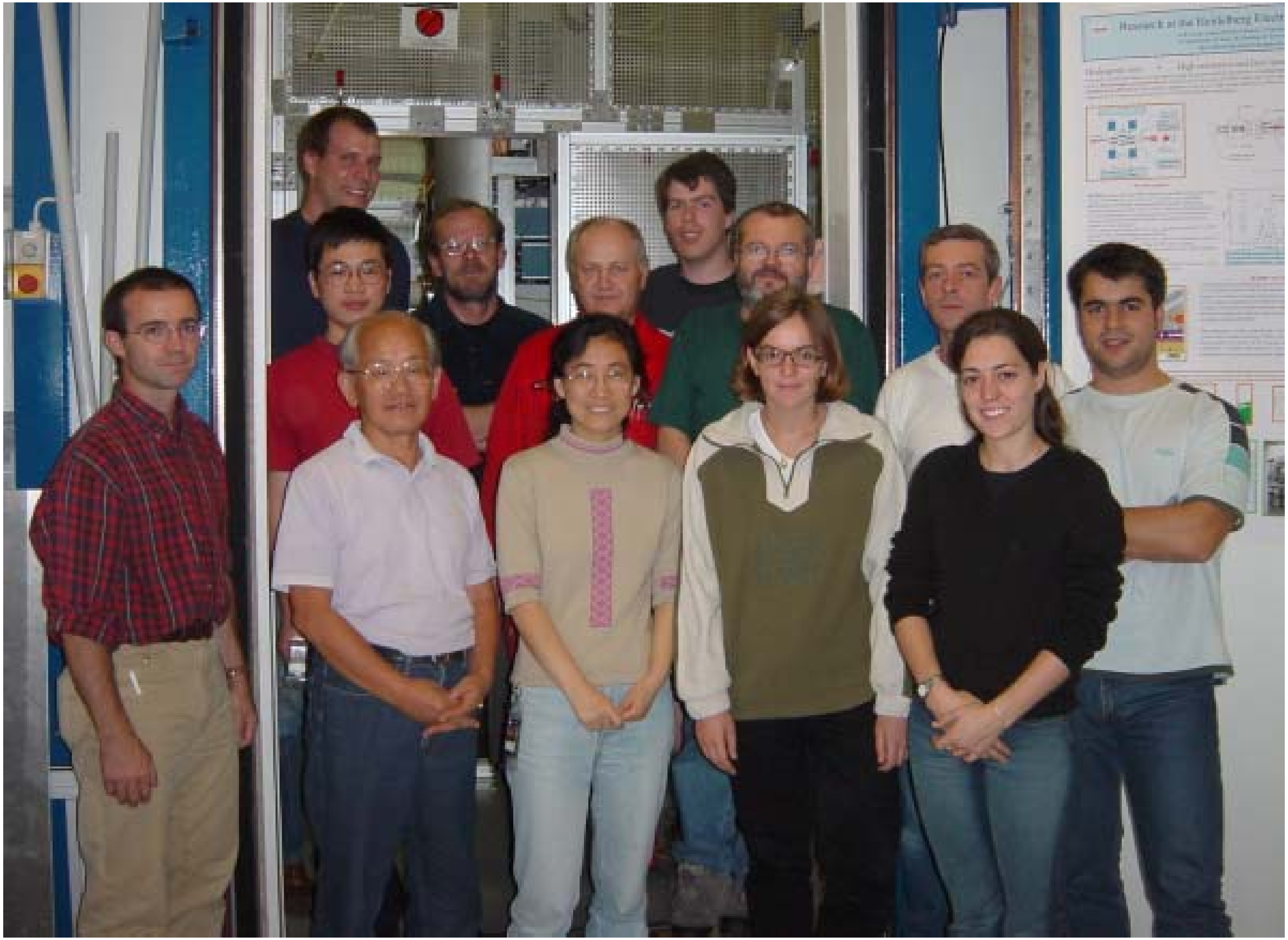
former members

Bhas Bapat (post doc)
Ilija Dragani≡ (PhD)
Panlin Guo (post doc)
Xuemei Zhang (post doc)
Andreas Werdich (diploma)

also involved, visitors

Bob DuBois
Bernold Feuerstein
Daniel Fischer
Robert Moshammer
Yaming Zou

Funding: HBFG, Land BW, DFG, Leibniz Award, MPG



the EBIT team